Solve oscillation problems when implementing op-amp power-booster stages

You can increase a low-level op amp's output voltage or current capability (or both) by employing a power-booster stage like the ones discussed in part 1 of this 2-part series. However, the additional phase shift introduced by including such a stage within an amplifier's feedback loop can increase the likelihood of oscillation, unless you judiciously apply frequency-compensation methods.

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To attain greater outputs from monolithic op amps with limited voltage and current capability, you must add a power-gain stage, such as one of those discussed in part 1 (**Ref 1**) of this 2-part series. But a circuit's overall phase shift, frequency response, and dynamic load-handling capabilities are critical when you include such a stage within an op amp's feedback loop. All feedback systems, including operational amplifiers, have gain and phase shift and, therefore, the propensity to oscillate. A booster stage's added gain and phase shift can cause poor ac response or outright oscillation. When applying such a stage, then, you must consider its gain and ac characteristics to ensure that your circuit achieves good dynamic performance.

A large body of complex mathematics is available that describes stability criteria and that can aid you in predicting stability characteristics of feedback amplifiers. The most sophisticated applications require this effort so that your circuits achieve optimum performance.

However, until now, little has appeared which discusses, in practical terms, how to understand and address the issues of compensating feedback amplifiers. Oscillation problems in amplifier/power-booster-stage combinations fall into two broad categories: local oscillations and loop oscillations. Local oscillations can occur in the boost stage, but they shouldn't appear in the IC op amp (which the manufacturer presumably debugged prior to sale). Transistor parasitics, layout, and CRT configurations cause these oscillations.

Usually, local booster-stage oscillations don't cause loop disruption. The major loop continues to function but contains artifacts of the local oscillation. In **Fig 1a** (which appeared as **Fig 8a** in **Ref 1**), the Q_3 and Q_5 and Q_4 and Q_6 pairs have a high gain-bandwidth product. The resistive feedback loops allow the pairs to oscillate in the 50- to 100-MHz region without the 100-pF/200Ω network shunting the dc-feedback resistors.

This network rolls off the transistors' gain-bandwidth product, preventing oscillation. It's worth noting that a ferrite bead in series with the 2-kΩ resistor will give similar results. In this case, the bead would raise the inductance of the wire, attenuating high frequencies.

Fig 1b depicts how the circuit would respond to a bipolar square-wave input if the local high-frequency,

If an output stage resides in an amplifier's feedback path, you must be concerned with the feedback loop's stability.
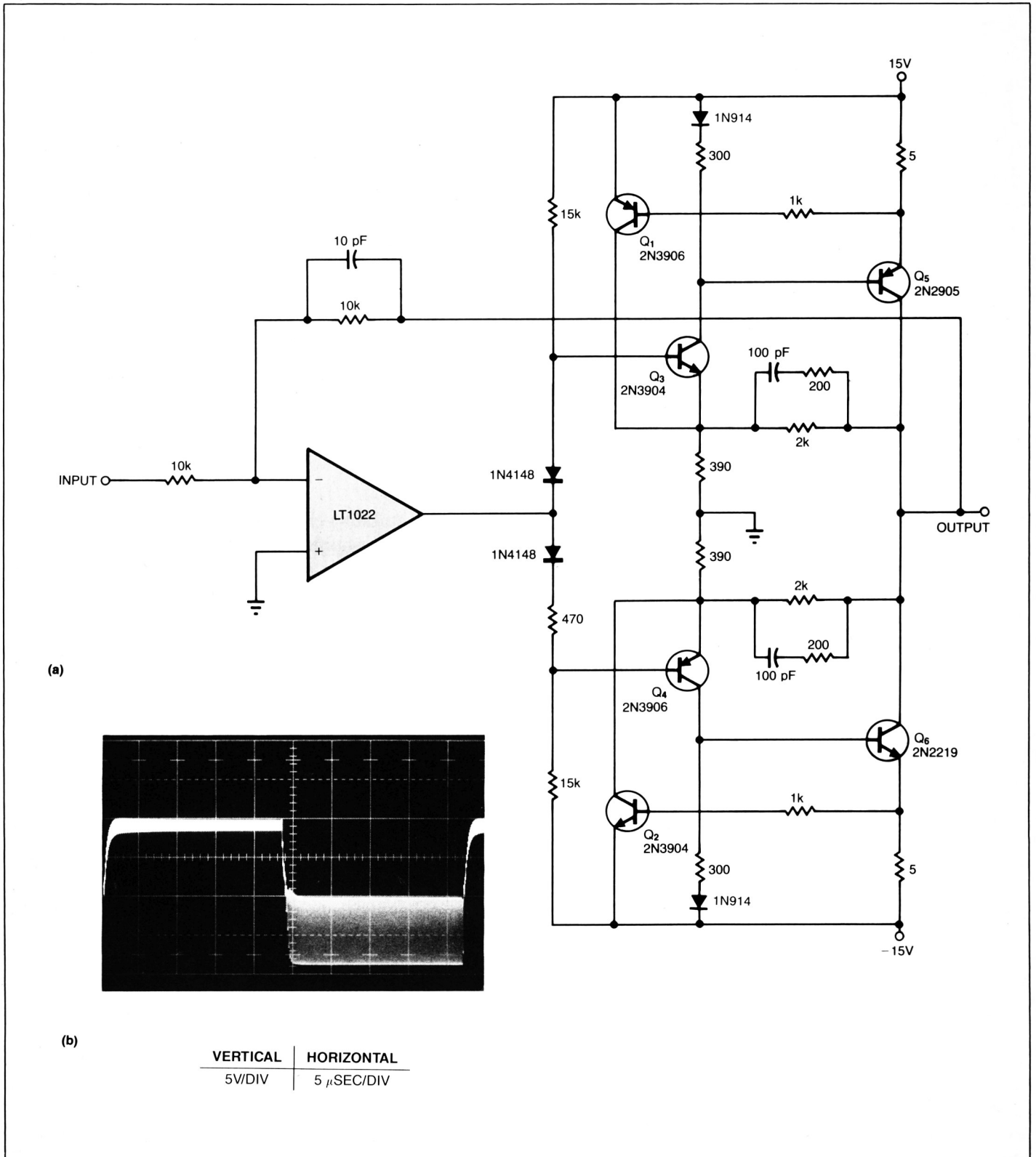

Fig 1—Removing the compensation networks of this circuit (**a**) and applying a bipolar-square-wave input results in high-frequency oscillation (**b**), which is typical of locally caused disturbances.

RC compensation networks were removed. The resultant high-frequency oscillation is typical of locally caused disturbances. Note that the major loop is functional, but the local oscillation corrupts the waveform.

Evaluate devices

You can help eliminate such local oscillations by selecting the proper device. Avoid high-f_T transistors unless you really need them. When you do use high-frequency devices, plan your layout carefully. In very stubborn cases, you may have to lightly bypass transistor junctions with small capacitors or RC networks.

Circuits that employ local feedback sometimes necessitate careful transistor selection and use. For example, transistors operating in a local loop may require different f_Ts to achieve stability. Emitter followers are notorious sources of oscillation, and you should never drive them directly from low-impedance sources.

The circuit in **Fig 2** (**Fig 5a** in **Ref 1**) employs 74C04 CMOS inverters instead of output transistors, but it too would exhibit local oscillation if it didn't include the RC damper network that's connected from the inverters' outputs to ground. The circuit forces the 74C04s to run in their linear region. Although the 74C04s' dc gain is low, their bandwidth is high. Therefore, with these ICs, very small parasitic-feedback terms result in high-frequency oscillations. The damper network provides a low-impedance path to ground at high frequencies, breaking up the unwanted feedback path.

Additional delay spurs loop oscillation

Loop oscillations arise when the added gain stage supplies enough delay to force substantial input-to-output phase shift. This phase shift causes the control amplifier to run too far out of phase with the gain stage. The control amplifier's gain combined with the added delay causes oscillation. Loop oscillations are usually relatively low in frequency, typically 10 Hz to 1 MHz.

A good way to eliminate loop-caused oscillations is to limit the gain-bandwidth product of the control amplifier. If the booster stage has a higher gain-bandwidth product than the control amplifier, its phase delay is easily accommodated in the loop.

If the control amplifier's gain-bandwidth product dominates, oscillation is inevitable. Under these conditions, the control amplifier hopelessly tries to servo a feedback signal that consistently arrives too late. The servo action takes the form of an electronic tail chase, with oscillation centered around the ideal servo point.
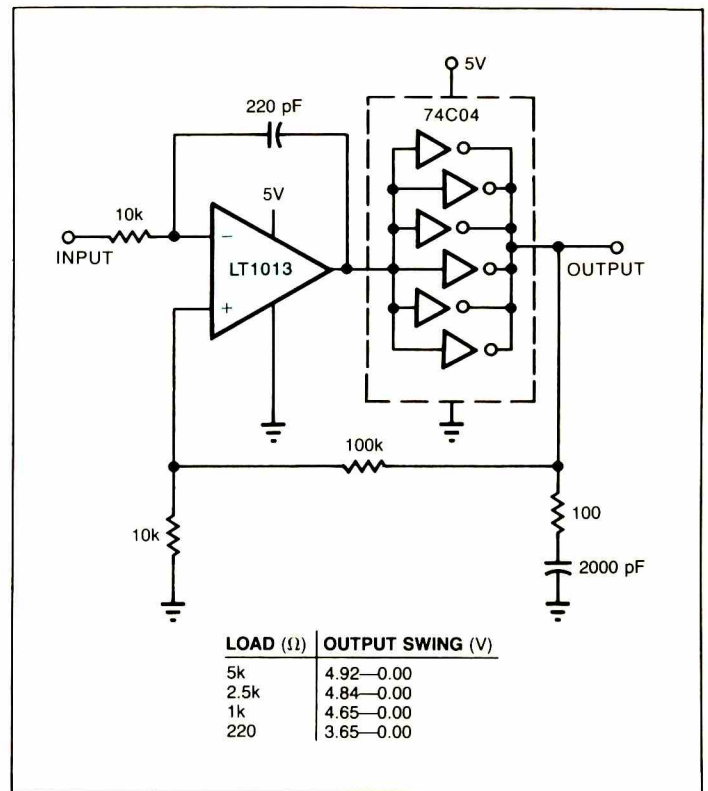
Frequency-response roll-off of the control amplifier

LOAD (Ω)	OUTPUT SWING (V)
5k	4.92—0.00
2.5k	4.84—0.00
1k	4.65—0.00
220	3.65—0.00

Fig 2—The RC damper network from the inverters' outputs to ground eliminates local oscillation.

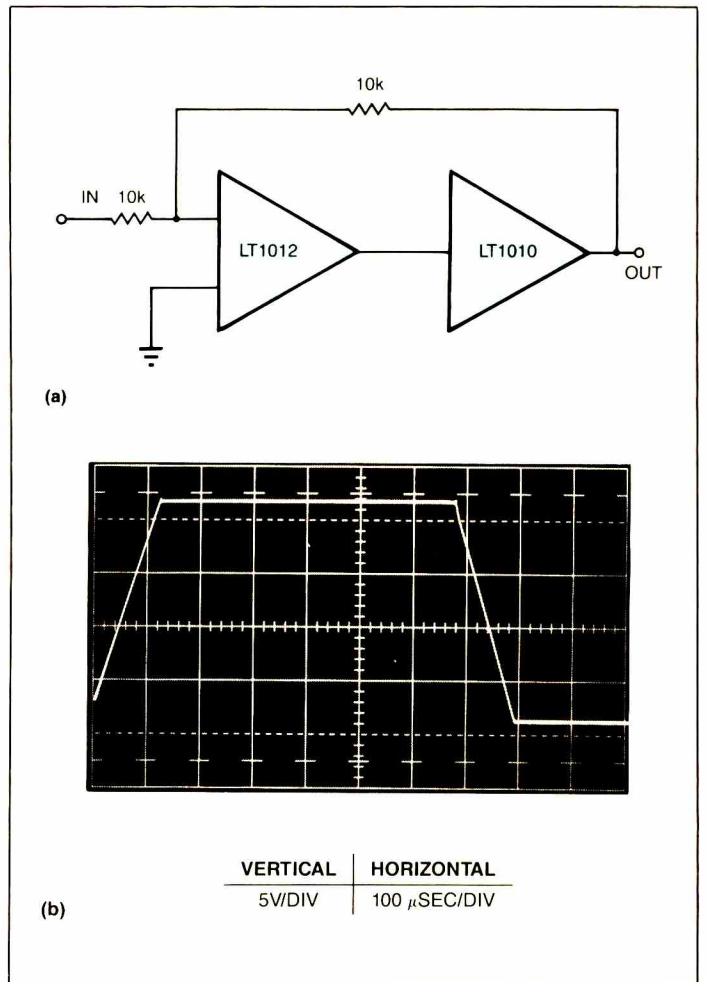| VERTICAL	HORIZONTAL
5V/DIV	100 μSEC/DIV

Fig 3—If a buffer amplifier has lower bandwidth than the control amplifier that drives it, you probably will not encounter high-frequency oscillation. The LT1012 is only a 600-kHz unit, whereas the LT1010 buffer is a 200-MHz device.
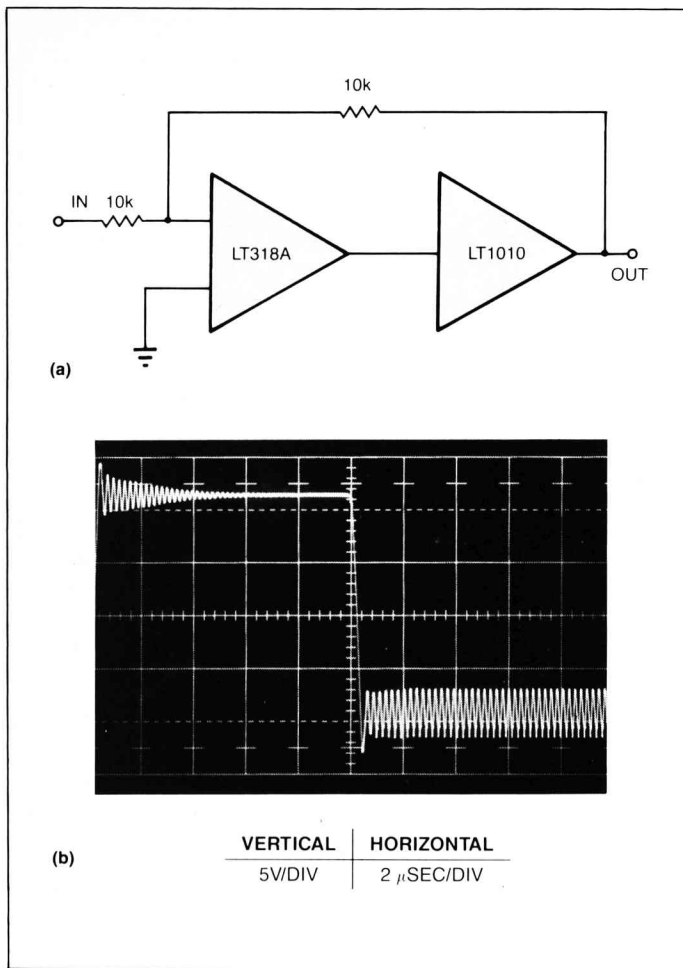
Fig 4—Substituting a 15-MHz LT318A for Fig 3's LT1012 results in high-frequency oscillation because the phase shift through the LTC1010 is now appreciable.

will almost always cure loop oscillations. In many situations, brute-force compensation—using large capacitors in the major feedback loop—provides the simplest solution. As a general rule, you can stabilize the loop by rolling off the control amplifier's gain-bandwidth product. The feedback capacitor serves to trim only step response; therefore, you shouldn't rely on it to stop outright oscillation.

The 600-kHz gain-bandwidth LT1012 amplifier used with the LT1010 current buffer produces the output shown in **Fig 3**. The LT1010's 20-MHz gain-bandwidth product introduces negligible loop delay, and waveform dynamics are clean. In this case, the LT1012's internal roll-off is well below the output stage's, and you achieve stability with no external compensation components.

Fig 4 uses a 15-MHz LT318A as the control amplifier. Here, the control amplifier's roll-off, close to the output stage's roll-off, causes problems. The phase shift through the LT1010 is now appreciable, and oscillation occurs. Stabilizing this circuit requires that you degenerate the LT318A's gain-bandwidth product.

The fact that the slower op-amp circuit doesn't oscillate is a key to understanding how to compensate booster loops. With the slow device, compensation is free. The faster amplifier makes the ac characteristics of the output stage significant and requires roll-off components for stability.

The high-voltage transistors in **Fig 5a** (**Fig 9a, Ref 1**) are very slow devices, and the LT1055 amplifier has a much higher gain-bandwidth product than the output stage. The 10-kΩ/100-pF network is locally compensated for by the LT1055, giving it an integrator-like response. This compensation, combined with the damping provided by the 33-pF feedback capacitor, affords good loop response.

Without any compensation components installed, the circuit oscillates (**Fig 5b**). The relatively slow oscillation frequency suggests a loop-oscillation problem. The RC components around the LT1055 degrade its gain-bandwidth product.

In this case, an RC time constant eliminates oscillations and gives the best possible response (**Fig 5c**) with no loop-feedback capacitor in place. Observe that the 1-μsec time constant selected offers significant attenuation at the oscillation frequency noted in **Fig 5b**. Finally, the loop-feedback capacitor selected (33 pF) gives the optimum damping, as depicted in **Fig 9b** of **Ref 1**.

When using compensation designs such as these, remember to investigate the effects of various loads and output operating voltages. Sometimes a compensation scheme that appears fine gives bad results for some output conditions. For this reason, you should check the compensated circuit over as wide a variety of operating conditions as possible. **EDN**

Reference

1. Williams, Jim, "Boost op-amp output without sacrificing drift and gain specs," *EDN*, May 29, pg 131.

Author's biography

Jim Williams, staff scientist at Linear Technology Corp (Milpitas, CA), specializes in analog-circuit and -instrumentation design. He has served in related capacities at National Semiconductor Corp, Arthur D Little Inc, and the Instrumentation Development Lab at MIT. A former student of psychology at Wayne State University, Jim enjoys tennis, art, and collecting antique scientific instruments.
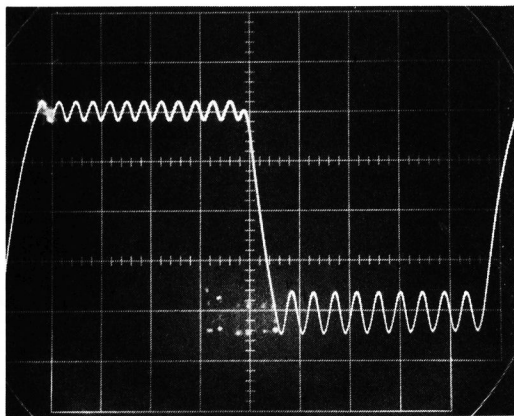
Article Interest Quotient (Circle One)
High 485 Medium 486 Low 487

(a)
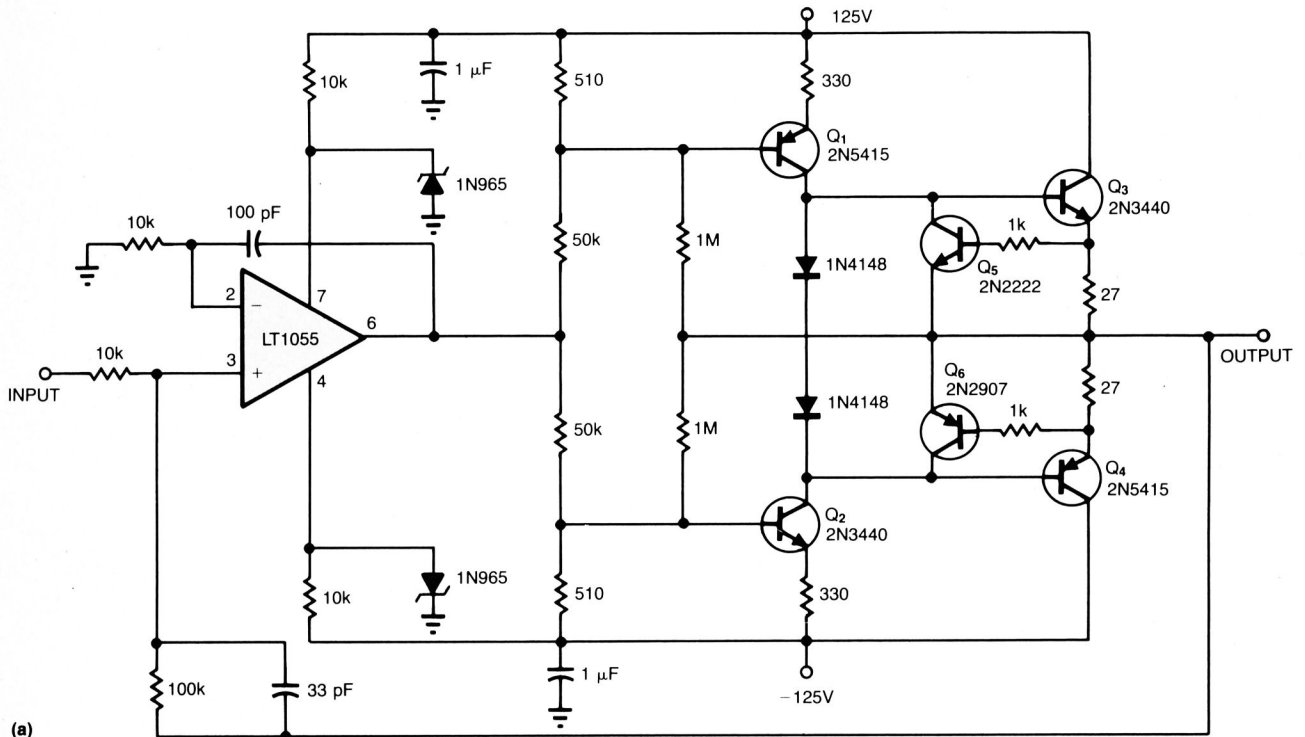
NOTE: OUTPUT TRANSISTORS REQUIRE HEAT SINKS.

(b)

VERTICAL	HORIZONTAL
50V/DIV	10 μSEC/DIV
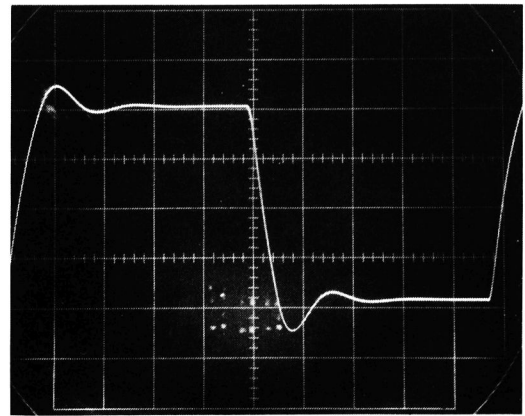
(c)

VERTICAL	HORIZONTAL
50V/DIV	10 μSEC/DIV

Fig 5—This circuit (a) oscillates (b) when no compensation components are installed. The relatively slow oscillation frequency suggests a loop-oscillation problem. With the attenuation components in place, the 1-μsec time constant yields both the best possible response and significant attenuation of the spurious oscillation **(c)**.